# Key points

Memoryless polynomial – at least in textbook form – cannot model AMPM

Cannot use baseband equivalents to model RF harmonics (I think this means we can’t use baseband equivalent models if we want to generate and analyze RF harmonics)

Can use baseband equivalents to model baseband harmonics

Cannot use AMAM to model any harmonics

IM2: I’m conflating what’s really happening on the chip – using SPDFT to estimate IM2 – vs. simply trying to model the nonlinearity using lowpass equivalents. These are different things. For lowpass equivalents, we just want to make sure the math works out identically to RF model; that’s why we want to maintain the relative powers.

**Typically, IM2 is important for the Rx**. Because of mixer nonlinearity and finite even-order distortion (mismatch in the differential circuits), the lowpass IM2 term is generated at the mixer output. The desired signal is frequency-translated to baseband, and the two terms overlap in frequency.

Even-order distortion is more of a baseband problem (IM2 in Rx, BBHD2 in Tx).

When simulating using the RF model instead of the baseband equivalent model, you must ensure that spurs do not land on top of each other. For example, RF harmonics may alias back into the intermodulation products of interest.

Typically, to determine the minimum spec for the intercept points, the average power of one tone in the two-tone test is set equal to the target power of the complex waveform (e.g. OFDM).

**Should the simulation for a complex baseband waveform be different from a two-tone waveform? I think it can be – you have some DC terms with the two-tone lowpass equivalent simulation, which is throwing you off, but that’s because you ignored the DC terms in the two-tone RF simulation.**

For the complex baseband waveform, the IM2 term captures all of the

This link says that to simulate with a real baseband signal, set Q signal to 0.

<https://www.mathworks.com/help/comm/ref/comm.memorylessnonlinearity-system-object.html>

# RF memoryless polynomial model

This is the basis for memoryless nonlinearity. However, this specific type of model is typically used for the receiver, e.g. to model IM2 and IM3.

IM2 is typically generated by the quadrature downconverter (finite mismatch in the differential outputs). IM3 can be generated by any stage. Everything ends up at baseband after downconversion. By measuring the tone amplitudes (fundamental, IM2, IM3), you can find the coefficients that model the entire Rx path.

Let’s say you apply two tones to the Rx input,

Ignoring out-of-band mixing products,

IM2 is already at baseband. Ignoring gain compression, let the baseband fundamental and IM3 be

Where the LO frequency is chosen s.t. none of the terms overlap (e.g. the LO can be well below the fundamental and IM3 terms).

Then the terms seen by

I don’t think the ¾ term matters. Ultimately IIP3 and IIP2 are determined by the power measurements, not by the formula. It’s just important to keep the formulas consistent between two-tone and complex waveform simulations.

## Complex baseband waveform

**RF model:**

A complex IQ waveform, at RF, is given by

and .

The RF memoryless polynomial model is

Plugging in,

We have the fundamental (desired), spectral regrowth, IM2, and RF harmonics.

**Lowpass equivalent model:**

Let’s translate and to their lowpass equivalents (with as the center frequency):

The terms with cannot be written in terms of . For the remaining terms,

We need to maintain the relative powers of the terms when translating to lowpass. Because we did not translate IM2, we need to scale it.

There is a power difference of 2, which means we can either scale the fundamental and third-order terms by or scale the IM2 term by .

Then the lowpass equivalent model is

## Two-tone waveform

**RF model:**

IIP2 and IIP3:

These intercept definitions are peak amplitude of one tone.

Typically, IIP2 and IIP3 are specified as average power of one tone.

**Lowpass equivalent model:**

The lowpass equivalent input signal is

The lowpass equivalent output signal is

What about the second-order term? It’s already a baseband signal, so there’s no conversion. However, we need to scale it by 2 so its amplitude, relative to the fundamental, remains the same.

If we only look at the positive frequencies, we have

Then the lowpass equivalent model is

Using the lowpass equivalent model to calculate IIP2 and IIP3 yields the same result as the RF model.

The DC term and the IM2 terms do not have the same relative powers as in the RF model. This seems to be one difference b/w two-tone simulation and complex waveform simulation. So then which model is correct?

I think we should compare desired and IM2 for the RF models.

Another thing is this is one fundamental to one IM2 (there are two fundamentals).

In complex waveform, you are getting the entire signal.

Remember, ultimately the only true model is the RF two-tone test. That is how to calculate the coefficients.

In the two-tone test, when you are measuring IM2, you will also be measuring the fundamental after downconversion. In our RF model, the fundamental is still at but that’s not actually true in measurement. In a two-tone test, where do we put the LO?

I think it’s fine if we put it in between the two tones. Let’s say the two tones are . Then at baseband, they are .

In any case, you are still measuring power in one tone.

In lowpass equivalent simulation with complex waveform, you are measuring the power of the entire desired signal. That’s a power factor of 2. The “IM2” term combines the DC and the low-frequency beats. (If you think of the complex waveform as the sum of a bunch of sinusoids – and pretty white spectrum too.)

Remember, the envelope term is not white at all. There is heavy DC in there.

Lowpass equivalent simulation of two-tone test is not exactly the same as RF model b/c of the DC term. But you can get a1, a2, a3 from this simulation. How to translate to complex waveform?

I think you should make the total signal power and the total DC+IM2 power the same in both lowpass equivalents. So

Complex:

Two-tone:

Total power of even-order terms is equal to , or equivalently an amplitude of

Total power of fundamental is or equivalently an amplitude of .

The question is how to assess the impact of IM2 in a lowpass equivalent simulation.

# Transfer curve models (AMAM-AMPM)

RF-only terms:

We saw that the lowpass equivalent model of the RF memoryless polynomial is given by

(Ignoring the second-order term, which is a baseband term.)

We can rewrite this as

The output is equal to the input scaled by an envelope-dependent gain. This is the idea behind AMAM, and by extension, AMPM.

The general AMAM-AMPM model is

.

Since this is a function only of envelope, I think the output of this model should have odd symmetry.

# Dynamic nonlinear models

GMP, DDR/Volterra, Hammerstein, Weiner

## Generalized memory polynomials (GMP)

and are the input and output of the DPD block. Let and be at full scale s.t. (normalized to the bitwidth).

When ,

In the digital front end, the output of the DPD block should be at full scale, which means that where is the bitwidth.

# AMAM-AMPM models (TBD)

Baseband equivalent

Instead of specifying nonlinear orders, specify a transfer curve

## Rapp

AMAM nonlinear model:

AMAM can only model terms like , like spectral regrowth in the RF amplifier.

It cannot model the RF harmonic in the RF amplifier or CIM3 in the baseband amplifier.

Rapp is one way of modeling AMAM:

Where is the linear amplifier gain, is the smoothness factor, and is the output saturation level.

## Saleh

AMPM nonlinear model:

Saleh is one way of modeling AMPM:

Where and are parameters to choose.

## Rapp-Saleh

AMAM-AMPM nonlinear model:

Rapp and Saleh can be combined to model AMAM-AMPM:

# Baseband amplifier as a memoryless polynomial

The derivation for a baseband amplifier is slightly different. Let , , and . Then

The complex signal after the baseband nonlinearity is :

The output terms are the signal, spectral regrowth, BBHD2, CIM3, and 2nd-order DC distortion.

As in the RF amplifier derivation, the strength of the nonlinear terms is a function only of the envelope amplitude .

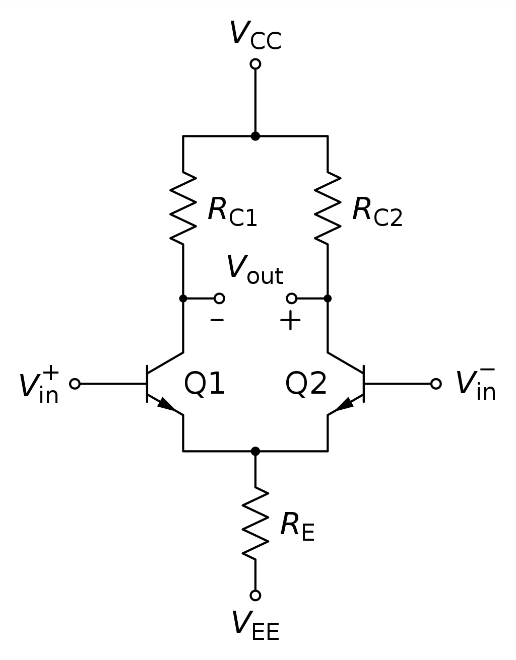
## Input intercept points?

## CIM3 (TBD)

Since CIM3 tends to be relatively low, can I just model it as ?

# Differential circuits to suppress even-order nonlinearity

We typically use differential circuits to suppress the even-order nonlinear terms. In a differential amplifier, the inputs are driven by signals of the same magnitude but opposite polarity. If the output is differential, the output is the difference between positive and negative terminals.



In our RF memoryless polynomial model, if the inputs are differential and driven by , we have

The 2nd-order term is cancelled if the “positive” and “negative” amplifiers are identical.

The same derivation applies separately to and paths in the baseband memoryless polynomial model.

# Cross modulation (TBD)

is desired, and are the interferers. Third-order nonlinearity will generate components at and . If is small, then the distortion products will be close to the signal frequency . This is actually the triple beat test.

# Triple beat (TBD)

# Cascaded IIP3

Let’s say your signal passes through multiple nonlinear systems, e.g.

For two stages,

Keeping only fundamental and 3rd-order terms, we have

Breaking down the terms, we have

1. : fundamental
2. : 3rd-order term from the first stage
3. : 3rd-order term from the second stage
4. : 2nd-order mixing in the second stage of (2nd-order term from first stage, fundamental)

Since and are generated by 3rd-order nonlinearity, these products are inband. However, involves mixing components at twice the fundamental, which are out of band. If we assume and add in phase while is suppressed, and we apply the equation for to the cascaded system response, we have

Extending to any number of stages, we have

Where is the IIP3 of the nth stage and is the fundamental voltage gain of the nth stage.

Large terms dominate the right-hand-side and in turn dominate the overall system . In an amplification chain, this means nonlinearity of later stages is more important than earlier stages. The of a stage is reduced by the gains of the previous stages:

# Cascaded IIP2 (TBD)